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(54) **FINDING OPTIMAL READ THRESHOLDS
AND RELATED VOLTAGES FOR SOLID
STATE MEMORY**

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Nov. 30, 2012, now Pat. No. 8,937,838.

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10, 2012.

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G11C 16/26 (2006.01)

(52) **U.S. Cl.**

CPC **G11C 16/26** (2013.01)

(58) **Field of Classification Search**

CPC G11C 16/28; G11C 11/5642

USPC 365/185.2, 189.15, 189.07

See application file for complete search history.

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365/45

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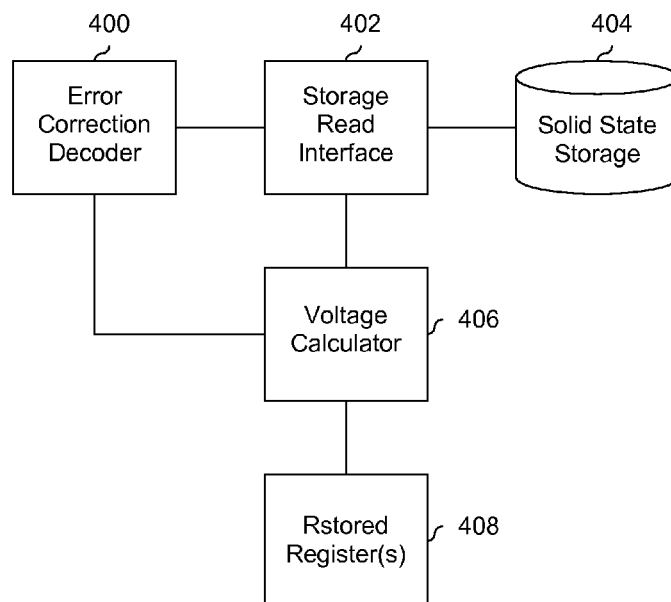
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(57) **ABSTRACT**

A read is performed using a first iteration of a read threshold voltage that is set to a default voltage to obtain a first characteristic. A second iteration of the read threshold voltage is generated using the default voltage and an offset. A read is performed using the second iteration of the read threshold voltage to obtain a second characteristic. A third iteration of the read threshold voltage is generated using the first and second characteristics. A read is performed using the third iteration of the read threshold voltage to obtain a third characteristic. It is determined if the third characteristic is one of the two characteristics closest to a stored characteristic. If so, a fourth iteration of the read threshold voltage is generated using the two closest characteristics.

15 Claims, 10 Drawing Sheets



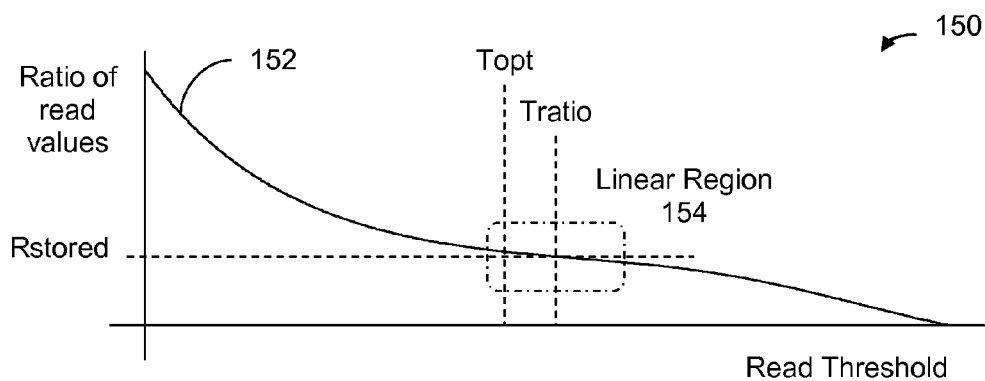
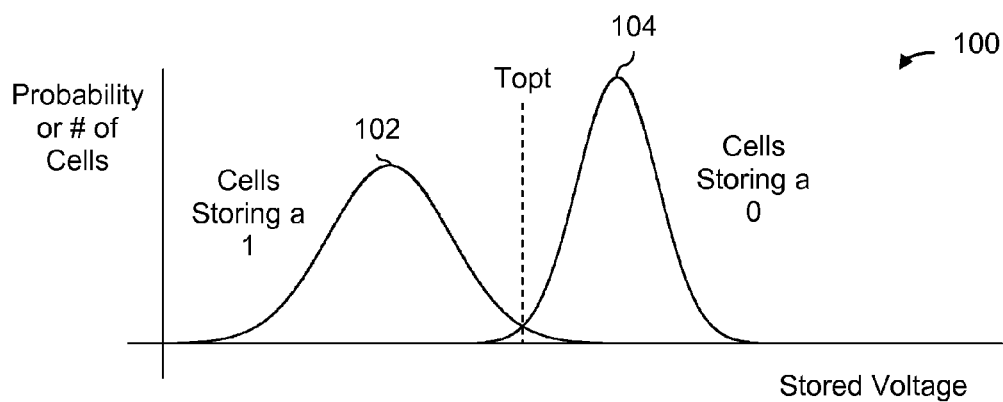


FIG. 1

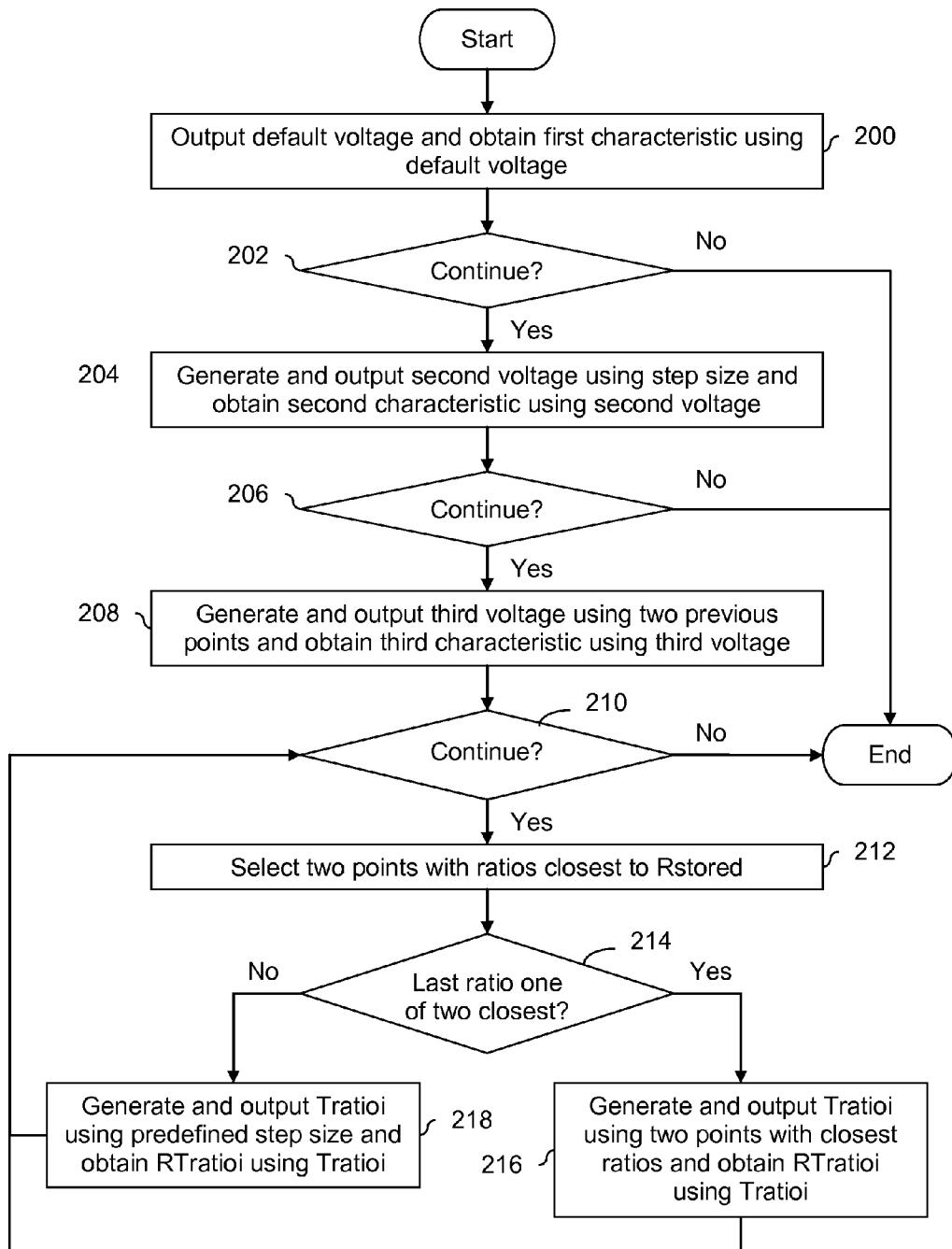


FIG. 2

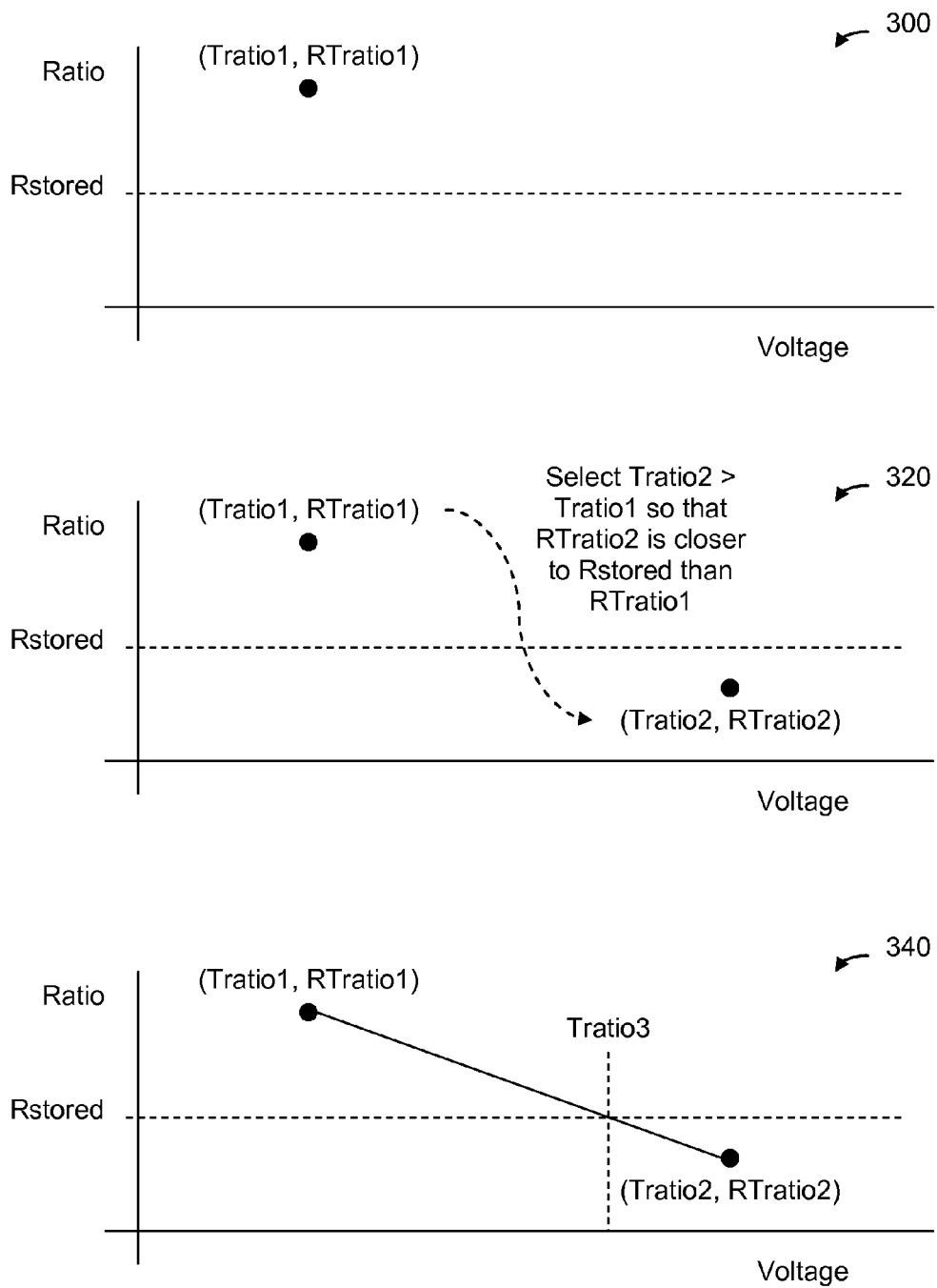


FIG. 3A

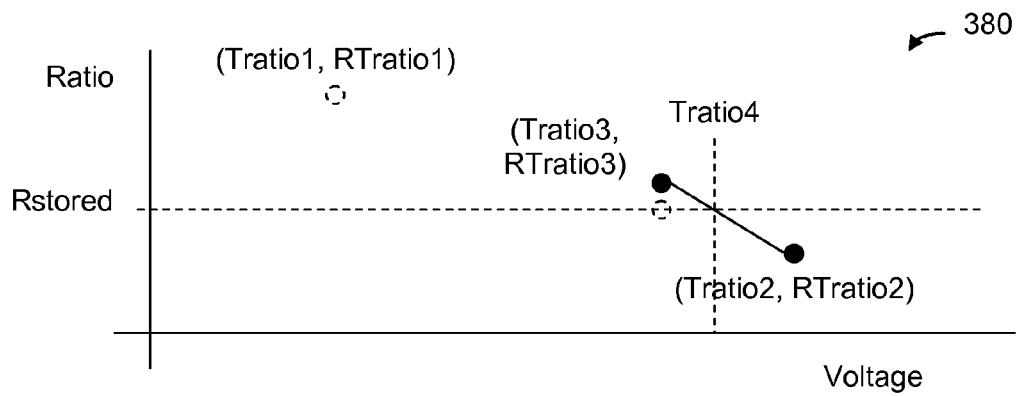
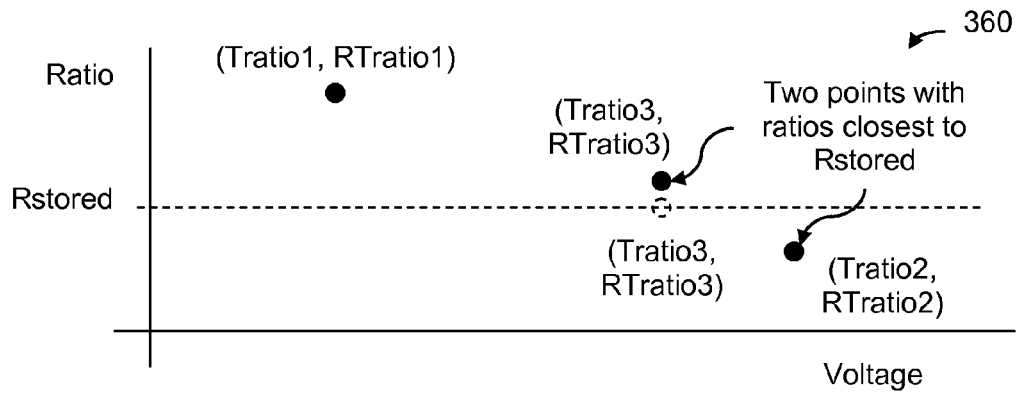
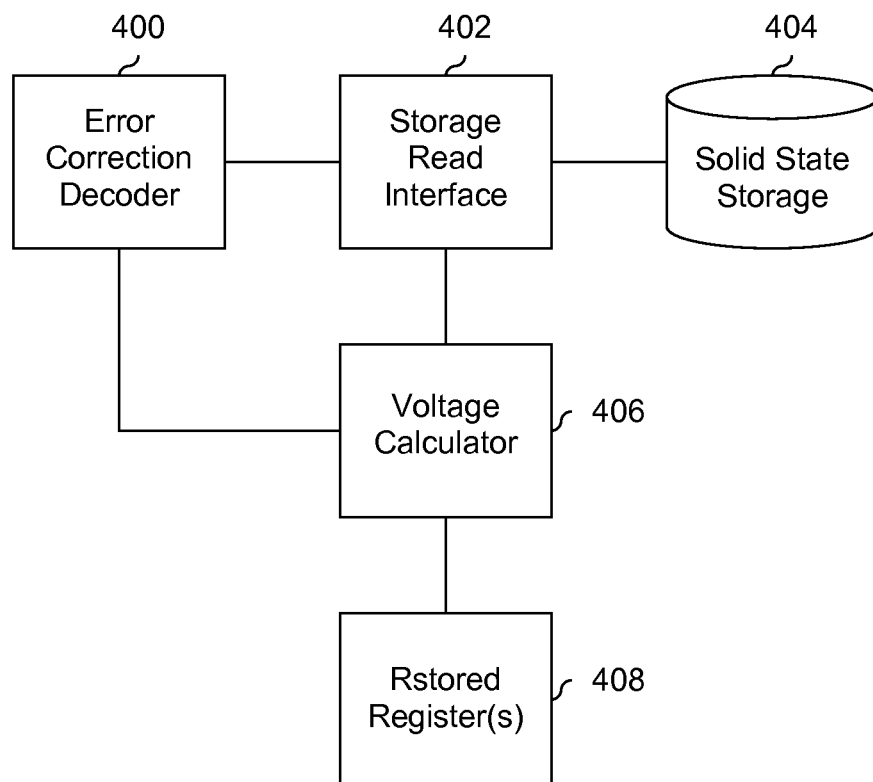


FIG. 3B

**FIG. 4**

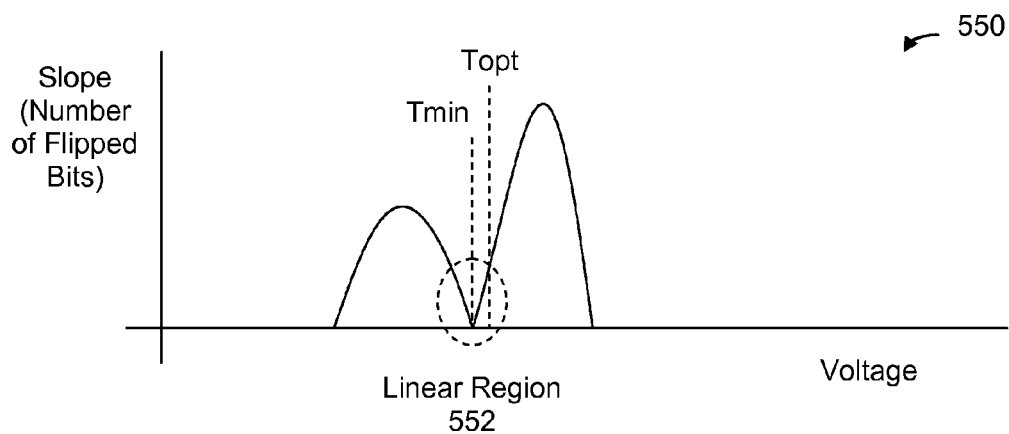
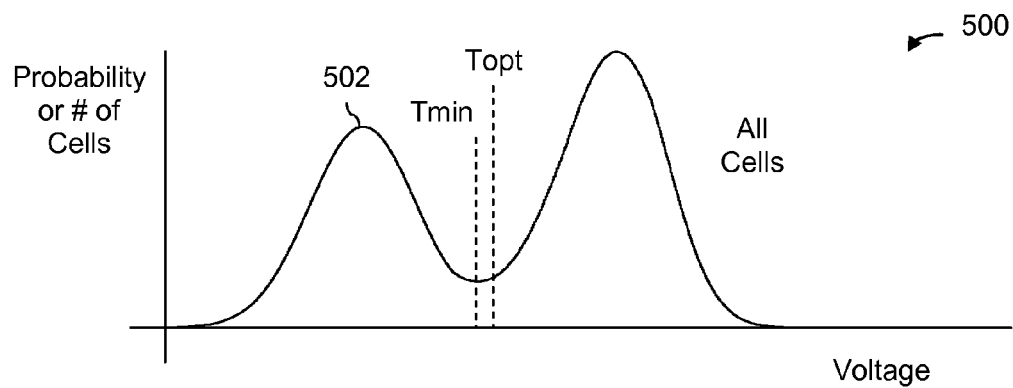


FIG. 5

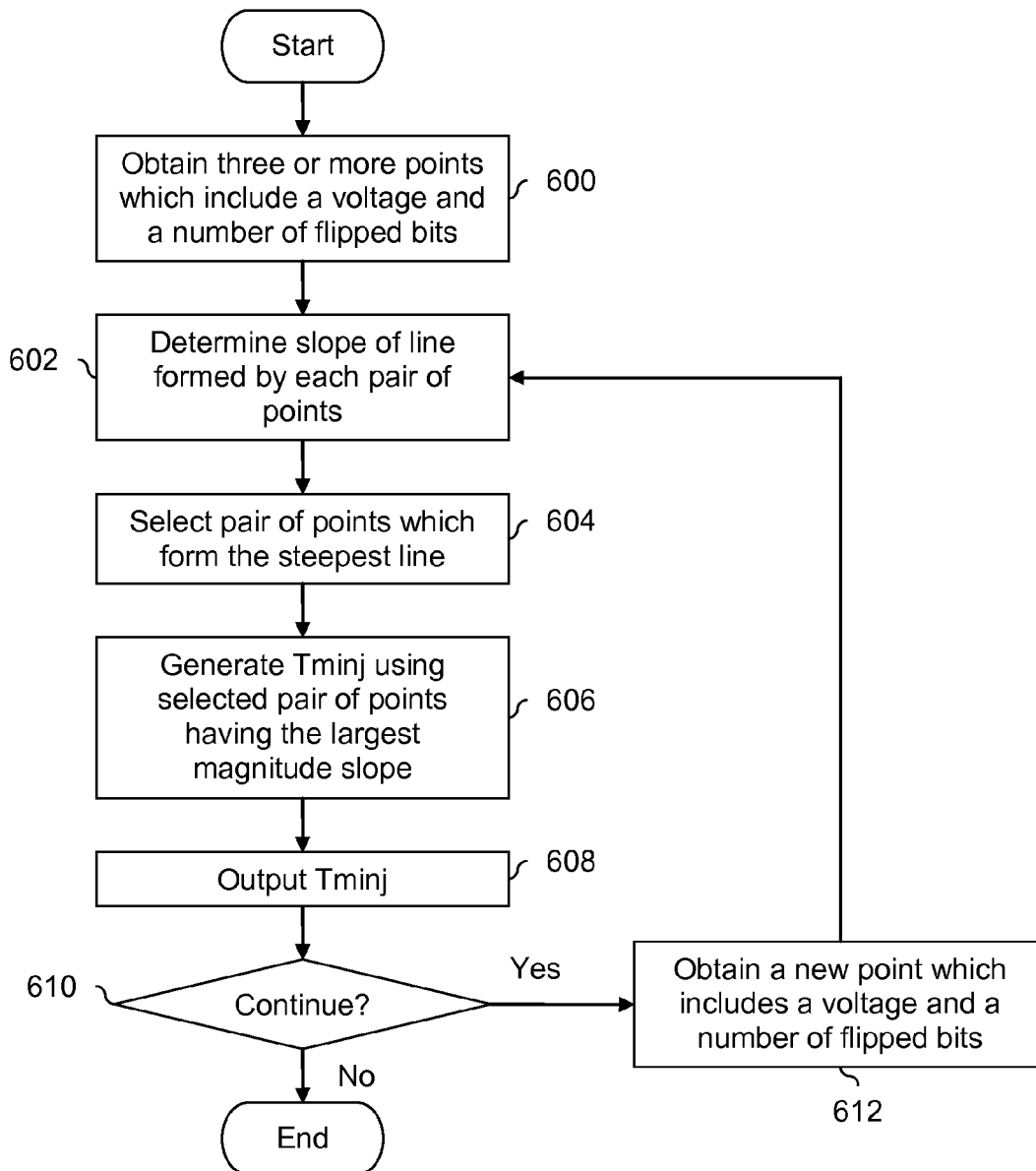


FIG. 6

700

Point Name	X (Voltage)	Y (Ratio)
R1	Tratio1	$R\text{Ratio1} = (Z\text{Ratio1})/(O\text{Ratio1})$
R2	Tratio2	$R\text{Ratio2} = (Z\text{Ratio2})/(O\text{Ratio2})$
R3	Tratio3	$R\text{Ratio3} = (Z\text{Ratio3})/(O\text{Ratio3})$
R4	Tratio4	$R\text{Ratio4} = (Z\text{Ratio4})/(O\text{Ratio4})$

720

Input Points	Point Name	X (Voltage)	Y (Slope or Number of Flipped Bits)
R1 and R2	S1	$X1 = (Tratio1 + Tratio2)/2$	$Y1 = (Z\text{Ratio2} - Z\text{Ratio1}) / (Tratio2 - R\text{Ratio1})$
R2 and R3	S2	$X2 = (Tratio2 + Tratio3)/2$	$Y2 = (Z\text{Ratio3} - Z\text{Ratio2}) / (Tratio3 - R\text{Ratio2})$
R3 and R4	S3	$X3 = (Tratio3 + Tratio4)/2$	$Y3 = (Z\text{Ratio4} - Z\text{Ratio3}) / (Tratio4 - R\text{Ratio3})$

740

Input Points	Slope of Lines Formed by S1, S2, and S3
S1 and S2	$(Y1 - Y2)/(X1 - X2)$ (Steepest Line)
S1 and S3	$(Y3 - Y1)/(X3 - X1)$
S2 and S3	$(Y3 - Y2)/(X3 - X2)$

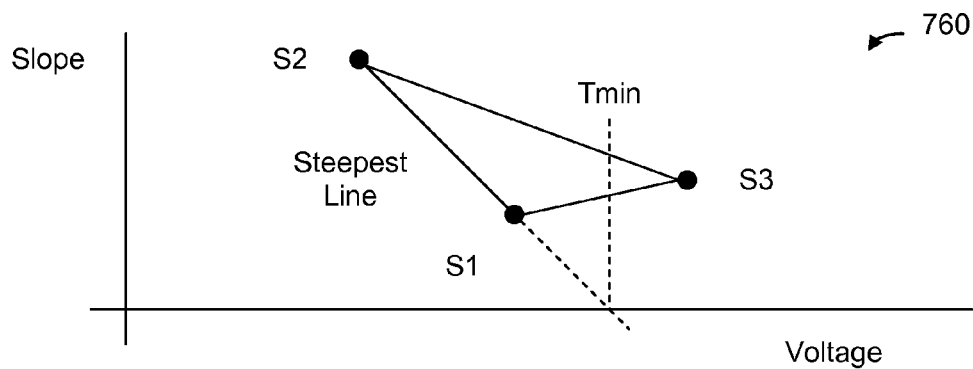
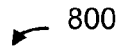


FIG. 7

 800

Topt Iteration #	Topt Generated (Used as Read Threshold)	Other Values Calculated and/or Stored
1	Topt1 = Tratio1	
2	Topt2 = Tratio2 = Tratio1 $\pm \Delta$	S1
3	Topt3 = Tratio3 (based on Tratio1 and Tratio2)	S1 and S2
4	If RTratio3 is one of two best ratios then Topt4 = Tratio4 (based on two Tratio values corresponding to best ratios) OR If RTratio3 is not one of two best ratios, then Topt4 = Tratiobest $\pm \Delta$	S1-S3
5	If RTratio4 is one of two best ratios then Topt5 = (Tratio5+Tmin5)/2 OR If RTratio4 is not one of two best ratios, then Topt5 = Tratiobest $\pm \Delta$	S1-S4, Tmin5

FIG. 8

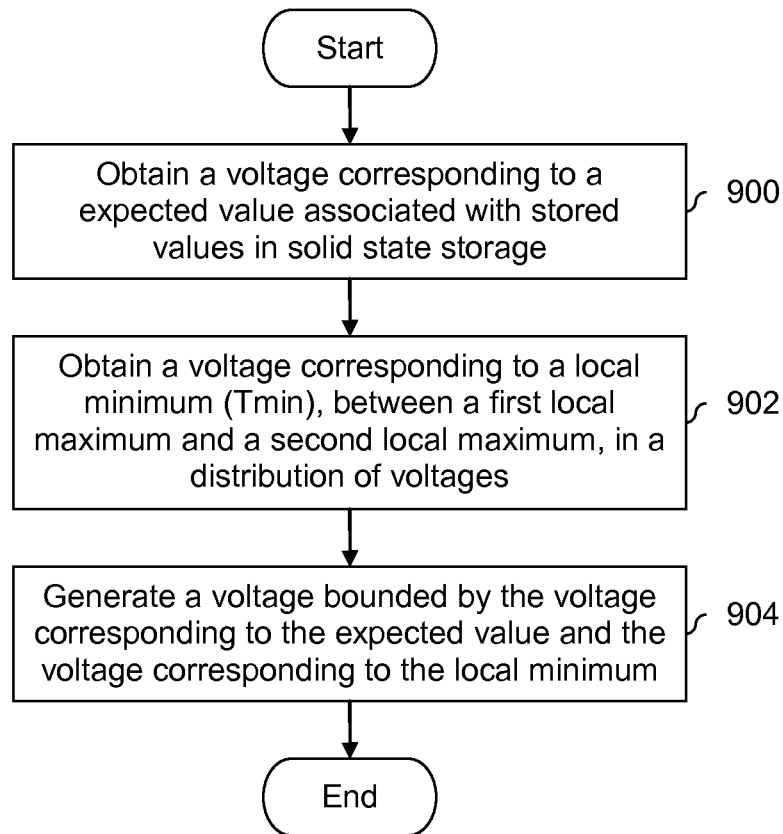


FIG. 9

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FINDING OPTIMAL READ THRESHOLDS AND RELATED VOLTAGES FOR SOLID STATE MEMORY

CROSS REFERENCE TO OTHER APPLICATIONS

This application is a continuation of co-pending U.S. patent application Ser. No. 13/691,113, entitled FINDING OPTIMAL READ THRESHOLDS AND RELATED VOLTAGES FOR SOLID STATE MEMORY filed Nov. 30, 2012 which is incorporated herein by reference for all purposes, which claims priority to U.S. Provisional Patent Application No. 61/585,174 entitled FINDING OPTIMAL READ THRESHOLDS IN NAND FLASH MEMORY filed Jan. 10, 2012 which is incorporated herein by reference for all purposes.

BACKGROUND OF THE INVENTION

When solid state memory (such as NAND Flash) is read, the returned value depends upon a read threshold. In an example single level cell (SLC) system where a cell stores a single bit, any cell which has a stored voltage lower than the read threshold is interpreted to store a 1 and any cell which has a stored voltage higher than the read threshold is interpreted to store a 0. The value of this read threshold therefore affects performance of the system. In general, it is desirable to develop techniques which improve the process by which a read threshold is determined and/or inputs which are used to determine a read threshold. Improving a read threshold would, for example, reduce the number of read errors and may enable some codewords (e.g., which are uncorrectable using an error correction code when a less optimal read threshold is used during the read process) to be decoded (e.g., because the reduced number of read errors now falls within the error correction capability of the code).

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments of the invention are disclosed in the following detailed description and the accompanying drawings.

FIG. 1 is a diagram showing an embodiment of distributions for cells storing zeros and ones and a ratio function associated with read-back values.

FIG. 2 is a flowchart illustrating an embodiment of a process for iteratively calculating Tratio.

FIG. 3A is a diagram showing an embodiment of data points used to generate a first, second, and third Tratio value.

FIG. 3B is a diagram showing an embodiment of data points used to generate a fourth Tratio value.

FIG. 4 is a diagram showing an embodiment of a storage system configured to iteratively calculate Tratio.

FIG. 5 is a diagram showing an embodiment of a distribution of a group of cells and a slope of that distribution.

FIG. 6 is a flowchart illustrating an embodiment of an iterative process for calculating Tmin.

FIG. 7 is a diagram showing an embodiment of data used to calculate Tmin.

FIG. 8 is a diagram showing an embodiment of optimal read thresholds (Topt) generated at various iterations.

FIG. 9 is a flowchart illustrating an embodiment of a process for generating a read optimal threshold.

DETAILED DESCRIPTION

The invention can be implemented in numerous ways, including as a process; an apparatus; a system; a composition

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of matter; a computer program product embodied on a computer readable storage medium; and/or a processor, such as a processor configured to execute instructions stored on and/or provided by a memory coupled to the processor. In this specification, these implementations, or any other form that the invention may take, may be referred to as techniques. In general, the order of the steps of disclosed processes may be altered within the scope of the invention. Unless stated otherwise, a component such as a processor or a memory described as being configured to perform a task may be implemented as a general component that is temporarily configured to perform the task at a given time or a specific component that is manufactured to perform the task. As used herein, the term 'processor' refers to one or more devices, circuits, and/or processing cores configured to process data, such as computer program instructions.

A detailed description of one or more embodiments of the invention is provided below along with accompanying figures that illustrate the principles of the invention. The invention is described in connection with such embodiments, but the invention is not limited to any embodiment. The scope of the invention is limited only by the claims and the invention encompasses numerous alternatives, modifications and equivalents. Numerous specific details are set forth in the following description in order to provide a thorough understanding of the invention. These details are provided for the purpose of example and the invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the invention is not unnecessarily obscured.

First, various embodiments for determining Texp and Tmin are described below. Texp is a voltage corresponding to an expected value (e.g., a count or ratio) associated with stored values in solid state storage. In some embodiments, Texp is Tratio, which is the voltage at which a group of cells in solid state storage, when read using Tratio as the read threshold, return values which match some (e.g., known or expected) ratio of stored or read-back values (e.g., ratio of ones to zeros, or ratio of zeros to ones, or the total number of ones, or the total number of zeros). Other embodiments of Texp include voltages corresponding to an expected number of read-back ones or zeros. Although some of the embodiments described herein use ratios or Tratio as an example, a number of expected zeros or ones may be used in some embodiments. Tmin is the voltage at which a local minimum (between a first local maximum and a second local maximum) occurs in a probability distribution function (PDF) or histogram of voltages which are stored by a group of cells.

Also described herein is a technique for estimating an optimal read threshold (Topt) using at least one of Texp and Tmin. (To distinguish between an estimate of the optimal read threshold and the optimal read threshold itself, the former is referred to herein as 'Topt' and the latter is referred to as Topt.) In some embodiments, one or both of Texp and Tmin are determined using the techniques described herein. Alternatively, some other technique may be used to obtain Texp and/or Tmin.

FIG. 1 is a diagram showing an embodiment of distributions for cells storing zeros and ones and a ratio function associated with read-back values. In diagram 100, the y-axis may be a probability (e.g., distributions 102 and 104 are probability distribution functions (PDFs)) or a number of cells (e.g., distributions 102 and 104 are histograms) showing what probability or number of cells have a particular stored voltage. Distribution 102 shows this for cells which (actually)

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store a one (e.g., regardless of what value is actually read back or interpreted) and distribution **104** shows this for cells which (actually) store a zero.

The optimal voltage with which to read a group of cells (e.g., a page of cells) having distributions **102** and **104** is T_{opt} . T_{opt} is the x-value at which distributions **102** and **104** intersect each other. However, distributions **102** and **104** are not typically known, so T_{opt} cannot be readily and/or directly obtained using distributions **102** and **104**.

Diagram **150** shows a distribution which is more readily available compared to distributions **102** and **104**. The y-axis of function **152** is a ratio of read-back values (e.g., a ratio of read-back ones to zeros or a ratio of read-back zeros to ones) and the x-axis is the read threshold used to obtain that particular ratio. In this example, the correct or actual ratio of zeros to ones (or ones to zeros) was stored when the group of cells associated with function **152** was written to; this ratio is R_{stored} . Oftentimes, because of the random nature of information and/or because of constraints applied to stored data, $R_{stored} \approx 0.5$. In the vicinity around R_{stored} (i.e., linear region **154**), function **152** is relatively linear and can be well approximated with a line. The following figures describe how the linearity of function **152** in linear region **154** can be taken advantage of in order to estimate $Tratio$.

As an aside, the distribution characteristics of distributions **102** and **104** are asymmetrical (e.g., the variances are not equal) and as a result $T_{opt} \neq Tratio$. If the two distribution characteristics matched then T_{opt} would equal $Tratio$. Although this example shows $T_{opt} < Tratio$, in some other embodiments this inequality is reversed.

Although the examples described herein are single level cell (SLC) examples, the technique may be extended to multilevel cell (MLC) systems. For example, if the binary values assigned are 11, 01, 00, and 10 (e.g., from left to right), then the techniques described herein may be used to determine a read threshold for the least significant bit (e.g., to distinguish between X0 and X1). The techniques described herein may also be used to determine a read threshold for the most significant bit (e.g., by dividing the voltage range in half and using distributions which only related to half of the voltage range (such as over 11 and 01 or over 00 and 10, but not both) and/or by using stored ratios which relate to the MSB and not the LSB).

As described above, although this example ratios are described (e.g., R_{stored} is a stored ratio and $Tratio$ is a voltage corresponding to R_{stored}), in some embodiments a number of stored ones or zeros may be used and similar techniques are used to find other T_{exp} values which are not $Tratio$. For example, the distribution of a number of zeros or a number of ones may also be linear around a stored number of ones/zeros, and thus similar techniques to those described herein may be used. In some cases, using ratios is preferred because the R_{stored} requires fewer bits to store than a number of stored zeros/ones which are stored in a given group of cells. The values of R_{stored} , for example, may typically remain close to 1 (e.g., because there typically is a relatively even number of ones and zeros) and so no matter how large the group of cells becomes, the number of bits to store R_{stored} stays relatively the same. In contrast, the number bits required to store a number of ones/zeros grows as the size of the group of cells grows.

FIG. 2 is a flowchart illustrating an embodiment of a process for iteratively calculating $Tratio$. The example of FIG. 2 will be explained using the examples of FIGS. 3A and 3B. FIG. 3A is a diagram showing an embodiment of data points used to generate a first, second, and third $Tratio$ value. FIG.

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3B is a diagram showing an embodiment of data points used to generate a fourth $Tratio$ value.

At **200**, a default voltage is output and a first characteristic is obtained using the default voltage. In diagram **300** in FIG. 3A, for example, the first characteristic is a ratio and the point at ($Tratio1$, $RTratio1$) shows one example of a default voltage which is output and a first characteristic which is obtained at **200**. In one example, if cells store voltages over a range of V_{min} and V_{max} , then $Tratio1 = (V_{max} - V_{min})/2$. In some embodiments, in addition to storing R_{stored} , a read threshold (e.g., corresponding to R_{stored}) is stored and that stored read threshold is used at **200**.

At **202**, it is determined whether to continue. For example, error correction decoding may be performed on data read back using $Tratio1$ as a read threshold. If error correction decoding is successful, then there may be no need to continue the process further (e.g., since the desired payload data in the error correction encoded data was able to be accessed).

If it is decided to continue at **202**, a second voltage is generated and output using a (e.g., predefined or calculated) step size (also referred to as an offset) and a second characteristic is obtained using the second voltage at **204**. In diagram **320**, for example, $Tratio2$ is selected to be greater than $Tratio1$ because this will result in a $RTratio2$ which is closer to R_{stored} than $RTratio1$. This is because (for this example at least) the slope of the ratio function (e.g., ratio function **152** in FIG. 1) is known to be negative and the value of R_{stored} is known. As such, since $RTratio1 > R_{stored}$ and the slope of the ratio function is negative, a $Tratio2$ which is greater than $Tratio1$ is selected. In some other embodiments, the slope of a ratio function is positive and $Tratio2$ is selected accordingly. In some embodiments, a predefined offset is used in selecting a $Tratio2$ value (e.g., $Tratio2 = Tratio1 + A$ where A is predefined).

At **206**, it is determined whether to continue. For example, the read values returned when using $Tratio2$ as a read threshold may be sufficient for an error correction decoder to successfully perform error correction decoding. If it is decided to continue at **206**, a third voltage is generated and output using the two previous points and a third characteristic is obtained using $Tratio3$ at **208**. In the example of diagram **340**, $Tratio3$ is the x-coordinate at which the line $y = R_{stored}$ intersects the line formed by ($Tratio1$, $RTratio1$) and ($Tratio2$, $RTratio2$). $RTratio3$ may be obtained by reading the group of cells using $Tratio3$ as the read threshold.

At **210**, it is determined whether to continue. If so, the two points with ratios closest to R_{stored} are selected at **212**. In diagram **360** in FIG. 3B, for example, the two points with closest ratios are ($Tratio3$, $RTratio3$) and ($Tratio2$, $RTratio2$) since $|RTratio1 - R_{stored}| > |RTratio2 - R_{stored}| > |RTratio3 - R_{stored}|$.

As shown in diagram **360**, linear approximation may not always match the real ratio function. $Tratio3$ was obtained using linear approximation. If the linear approximation were perfect (i.e., the ratio function equaled the linear approximation for all points over a range of interest), then reading the group of cells with $Tratio3$ would yield a ratio of R_{stored} (i.e., the point is shown with a dashed outline in diagram **360**). In actuality, however, the linear approximation is not perfect (i.e., the ratio function does not equal the linear approximation over all points in the range of interest) and reading the group of cells with $Tratio3$ as the read threshold yields a ratio of $RTratio3$ where $RTratio3 > R_{stored}$. For visual clarity, ($Tratio3$, $RTratio3$) and ($Tratio3$, R_{stored}) are shown with a noticeable gap between the two points but in actuality the points may be relatively close; the diagrams shown herein are not necessarily to scale.

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It is determined at **214** if the last ratio is one of the two closest. For example, in diagram **360**, the last ratio is RTratio3. Since (Tratio3, RTratio3) was one of the points selected at **212**, the decision at **214** is in the affirmative. If the decision at **214** is Yes then Tratioi is generated and output using the two points with the closest ratios and RTratioi is obtained using Tratioi. For example, in diagram **380**, Tratio4 is the x-coordinate of the intersection of $y=R_{\text{stored}}$ and the line formed by (Tratio3, RTratio3) and (Tratio2, RTratio2). Step **216** is similar to step **208**.

If the decision at **214** is No then Tratioi is generated and output using a predefined step size (or offset) and RTratioi is obtained using Tratioi. Step **214** is similar to step **204**. In some embodiments, a predefined step size is added or subtracted from voltage (i.e., x value) of the point with the ratio (i.e., y value) closest to Rstored. Whether the predefined step size is added or subtracted is selected based on which direction will cause the next or resulting ratio to be closer to Rstored (e.g., similar to step **204**).

After steps **218** or **216**, it is decided whether to continue at **210**.

In some embodiments, there may be no stored ratio (e.g., Rstored) value, no stored number of zeros (e.g., Zstored), or stored number of ones (e.g., Ostored). For example, a system may simply not store this parameter, or the value is stored but it is inaccessible or corrupted. In some such embodiments, a default or predefined ratio is used. For example, a default ratio of 0.5 may be used. The random nature of stored data and/or modulation codes applied to stored data may result in stored data that tends to be equally split between zeros and ones. Ratios of stored values (e.g., which include both stored ratios and default ratios) or numbers of stored ones/zeros, are referred to generally herein as expected ratios. Similarly, numbers or counts of stored zeros/ones (e.g., where an actual value stored at the time a group of cells is written to, or an estimated value in the event no value stored at the time of writing is available) are referred to generally herein as expected numbers or counts (e.g., of zeros/ones).

FIG. **4** is a diagram showing an embodiment of a storage system configured to iteratively calculate Tratio. In some embodiments, voltage calculator **406** performs at least some of the steps shown in FIG. **2**. Storage read interface **402** may be used to perform reads (e.g., at steps **200**, **204**, and **212**) in FIG. **2**. In some embodiments, some or all of the modules shown are implemented using semiconductor components, such as an application-specific integrated circuit (ASIC) or a field-programmable gate array (FPGA).

In the example shown, data is stored on solid state storage **404** (e.g., NAND Flash). Storage read interface **402** is used to access the data stored on solid state storage **404** and takes as input a read threshold (e.g., Tratioi) and read address(es) and returns the read data. In some embodiments, voltage calculator **406** generates (iteratively, if more than one iteration is desired) Tratio values using Rstored values kept in Rstored register(s) **408** and by obtaining ratios (e.g., RTratio1, RTratio2, etc.) by performing reads via storage read interface **402**. In some embodiments where voltage calculator **406** is configured to output Tratio values, those Tratio values are passed from voltage calculator **406** to error correction decoder **400**. In one example, error correction decoder **400** is an LDPC decoder. Using the supplied Tratio values, error correction decoder **400** obtains read values from solid state storage **404** via storage read interface **402**. In the event error correction decoding of the read values fails, error correction decoder **400** instructs voltage calculator **406** to re-generate another Tratio.

In some embodiments, voltage calculator **406** calculates (e.g., iteratively) Tmin values. In some embodiments, voltage

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calculator **406** calculates (e.g., iteratively) Topt values, for example based on a Tmin value and/or a Tratio value.

FIG. **5** is a diagram showing an embodiment of a distribution of a group of cells and a slope of that distribution. In diagram **500**, the y-axis of distribution **502** may be a probability (in which case distribution **502** is a PDF) or a number of cells (in which case distribution **502** is a histogram) having particular stored voltage. Distribution **502** shows this for all cells in a group; distribution **502** does not necessarily know which cells are actually storing a one versus a zero.

The voltage at which distribution **502** has a local minimum is called Tmin. As a result of asymmetrical distribution characteristics in cells actually storing a one versus a zero (e.g., the variances are not equal), $T_{\text{min}} \neq T_{\text{opt}}$. In this particular example $T_{\text{min}} < T_{\text{opt}}$ but in some other embodiments this ordering may be reversed.

Diagram **550** shows the slope of distribution **502** between the two local maxima. At the two local maxima and the local minimum at Tmin in distribution **502**, the slope is zero. In the region around Tmin (linear region **552**), slope function **550** is substantially or almost linear. Another thing to note about diagram **550** is that it shows, for a given read voltage, how many bits would flip if the read voltage were "wiggled" by an infinitesimally amount. For example, each point on distribution **502** shows how many cells in a group of cells would be read or interpreted as being "flipped" if the read threshold at a given voltage were changed by a small amount (e.g., $V+\delta$ or $V-\delta$). If one point on distribution **502** is (1 V, 3 one-to-zero flips), then three cells in the group are just barely being read or interpreted as ones (e.g., because they are at 0.999 V) and decreasing (as an example) the read voltage by just a little would cause those cells to be read or interpreted as a zero. The following figures described embodiments in which the linear nature of the slope function around Tmin and a number of flipped bits are used to generate Tmin.

FIG. **6** is a flowchart illustrating an embodiment of an iterative process for calculating Tmin. The example of FIG. **6** will be explained using the example of FIG. **7**. FIG. **7** is a diagram showing an embodiment of data used to calculate Tmin.

At **600**, three or more points are obtained which include a voltage and a number of flipped bits. In some embodiments, the points are obtained at **600** by reading a group of cells at various read thresholds and recording the number of read-back zeros and/or number of read-back ones corresponding to those read thresholds. In some embodiments, data associated with calculating a Tratio value is used in obtaining points at **600**. Table **700** in FIG. **7**, for example, may show points and/or data from FIGS. **3A** and **3B**. The y coordinates of the points in table **700** are ratios of read back values and in this example are ratios of zeros to ones (alternatively, a ratio may be a ratio of ones to zeros) where ZTratio is the number of cells read as having a zero (for a particular read threshold) and OTratio is the number of cells read as having a one (for that same read threshold).

Using the data shown in table **700**, the points shown in table **720** are obtained. Points S1, S2 and S3 in table **720** are an example of points obtained at **600** in FIG. **6**. The coordinates of point S1 are obtained using data from points R1 and R2, the coordinates of point S2 are obtained using data from points R2 and R3, and the coordinates of point S3 are obtained using data from points R3 and R4. For example, as each iteration of a Tratio generation process is performed, the read back number of zeros or ones (e.g., ZTratio or OTratio) at each iteration is recorded and the two most recent number of read back values is used. Although this example shows the number of flipped bits calculated using a change in a number of zeros, a

change in a number of ones may be used. In this example, the x-coordinate in table 720 is the mean or midpoint of x-coordinates of the two input points; in some other embodiments some other x-coordinate value may be used. For example, instead of having $X1$ be $(Tratio1 + Tratio2)/2$, $X1$ may be the x-coordinate of $Tratio1$ or the x-coordinate of $Tratio2$. Referring back to diagram 550 in FIG. 5, points S1, S2 and S3 from table 720 are points on the slope function shown in diagram 550.

The slope of a line formed by each pair of points is determined at 602 and the pair of points which form the steepest line is selected at 604. Table 740 shows the slope of lines formed by S1, S2, and S3 and diagram 760 shows this graphically. In this example, assume that $X2 < X1 < X3$ and $Y1 < Y3 < Y2$. As such, the line with the steepest slope (i.e., largest magnitude) is the line formed by S1 and S2. The sign of the slope is not taken into consideration when finding the steepest slope at 604 and a line with a steepest slope may be increasing (i.e., sign of slope is positive) or decreasing (i.e., sign of slope is negative).

$Tminj$ is generated using the selected pair of points having the largest magnitude slope at 606 and $Tminj$ is output at 608. As shown in diagram 760, $Tmin$ is the x-coordinate at which the line $y=0$ intersects the line formed by S1 and S2.

It is determined at 610 whether to continue. For example, an error correction decoder may successfully decode and it is not necessary to generate more $Tminj$ values. If it is decided to continue at 610 then a new point is obtained which includes a voltage and a number of flipped bits at 612 and the slope of a line formed by each pair of points is determined at 602. In some embodiments, a new point is obtained at 612 using data used in generating a $Tratio$ value (see, e.g., diagrams 700 and 702). In some embodiments, previously-calculated slopes generated at 602 are stored so that they do not need to be re-generated the next time step 602 is performed. In such

embodiments, only slopes for lines which include a newly-obtained point (e.g., obtained at 612) are calculated at 602. FIG. 8 is a diagram showing an embodiment of optimal read thresholds ($Topt$) generated at various iterations. In the example shown, the optimal read thresholds are used as a read threshold to read a group of cells in solid state storage. Although table 800 shows five iterations of an optimal read threshold, in some cases a system may not necessarily be requested to (re)generate that many optimal read threshold values. In some embodiments, the technique used to generate $Topt$ for iterations 6 and greater (if desired) is the same as iteration #5.

At the first iteration in table 800, the optimal read threshold generated is a $Tratio$ value at a first iteration. For example, a default $Tratio1$ output may be output as in step 200 in FIG. 2. At the second iteration, the optimal read threshold generated is generating by adding or subtracting an offset or step size (Δ) to the optimal read threshold from the first iteration. See, for example, step 204 in FIG. 2 where an offset is added in a direction that is expected to produce a ratio that is closer to an expected ratio (e.g., $Rstored$ or a default ratio if no ratio is stored). Also at the second iteration, a point S1 (e.g., where one coordinate is a voltage and the other coordinate is a number of bits flipped) is generated and stored. Examples of point S1 are shown in FIG. 7.

At the third iteration, there are two previous $Tratio$ values available (i.e., $Tratio1$ and $Tratio2$) and those values are used to generate the third optimal read threshold. See, for example, step 208 in FIG. 2. The point S2 is also generated and stored during the third iteration. In some embodiments, the process described in FIG. 6 is used to generate S2 (e.g., including by selecting a steepest slope).

At the fourth iteration, the optimal read threshold generated depends on whether the last ratio of read-back values (i.e., $Rratio3$) obtained using the last optimal read threshold (i.e., $Tratio3$) is one of the two best ratios. For example if $|Rratio1 - Rstored| < |Rratio3 - Rstored|$ AND $|Rratio2 - Rstored| < |Rratio3 - Rstored|$, then the last ratio is not one of the two best ratios because $Rratio1$ and $Rratio2$ are closer to $Rstored$ than $Rratio3$. If the last ratio is one of the best ratios, then $Topt4 = Tratio4$ which is based on the two $Tratio$ values corresponding to the two best ratios. See, for example step 216 in FIG. 2. If not, an offset or step size is added/subtracted to the voltage corresponding to the best ratio. See, for example, step 218 in FIG. 2.

In the fifth iteration, the process is similar to that in the fourth iteration if the last ratio is not one of the two best ratios. However, if the last ratio is one of the two best ratios, then the optimal read threshold for the fifth iteration is an average of the $Tmin$ and $Tratio$ value. In this particular example, the technique used to generate $Tmin5$ needs at least S1-S3 and therefore a $Tmin$ value is not available until the fifth iteration because all of S1-S3 are not available during the fourth iteration but only after the fourth iteration concludes. In other embodiments where $Tmin$ is available earlier, $Tmin$ may be used in generating the optimal read threshold in an earlier iteration.

FIG. 9 is a flowchart illustrating an embodiment of a process for generating a read optimal threshold. At 900, a voltage corresponding to an expected value associated with stored values in solid state storage is obtained. In some embodiments, the example process shown in FIG. 2 is used to obtain $Tratio$ at 900. Alternatively, some other technique (e.g., not described herein) may be used to obtain the voltage at 900 (e.g., a voltage corresponding to an expected number of zeros/ones). At 902, a voltage corresponding to a local minimum ($Tmin$), between a first local maximum and a second local maximum, in a distribution of voltages is obtained. In diagram 500 in FIG. 5, for example there are three local minima; the local minimum in the middle is between two local maxima. In some embodiments, step 902 is performed using the example process described in FIG. 6. Alternatively, some other technique (e.g., not described herein) may be used. At 904, a voltage bounded by the voltage corresponding to the expected value and the voltage corresponding to the local minimum is generated. In the example of FIG. 5, $Tmin < Topt$ and in the example of FIG. 1, $Tratio > Topt$ and thus using $Tratio$ and $Topt$ as bounds for $Tratio$ may be a good choice for estimating or generating $Topt$. In some embodiments, the average of $Tmin$ and $Tratio$ is used as $Topt$.

Although the foregoing embodiments have been described in some detail for purposes of clarity of understanding, the invention is not limited to the details provided. There are many alternative ways of implementing the invention. The disclosed embodiments are illustrative and not restrictive.

What is claimed is:

1. A method, comprising:

- performing a read of solid state storage, using a first iteration of a read threshold voltage that is set to a default voltage, in order to obtain a first characteristic associated with the first iteration of the read threshold voltage;
- using a processor to generate a second iteration of the read threshold voltage based at least in part on the default voltage and an offset;
- performing a read of the solid state storage, using the second iteration of the read threshold voltage, in order to obtain a second characteristic associated with the second iteration of the read threshold voltage;

using the processor to generate a third iteration of the read threshold voltage based at least in part on the first characteristic and the second characteristic;
 performing a read of the solid state storage, using the third iteration of the read threshold voltage, in order to obtain a third characteristic associated with the third iteration of the read threshold voltage;
 selecting, from (1) the first characteristic, (2) the second characteristic, and (3) the third characteristic, the two characteristics that are closest to a stored characteristic, determining if the third characteristic is one of the two characteristics that are closest to the stored characteristic; and

in the event it is determined that the third characteristic is one of the two characteristics that are closest to the stored characteristic, using the processor to generate a fourth iteration of the read threshold voltage based at least in part on the two characteristics that are closest to the stored characteristic.

2. The method of claim 1, wherein the first characteristic, the second characteristic, the third characteristic, and the stored characteristic include one or more of the following: a ratio of ones to zeros or a ratio of zeros to ones.

3. The method of claim 1, wherein the first characteristic, the second characteristic, the third characteristic, and the stored characteristic include one or more of the following: a number of ones or a number of zeros.

4. The method of claim 1 further comprising: in the event it is determined that the third characteristic is not one of the two characteristics that are closest to the stored characteristic, using the processor to generate the fourth iteration of the read threshold voltage based at least in part on the offset.

5. The method of claim 4, wherein in the event it is determined that the third characteristic is not one of the two characteristics that are closest to the stored characteristic, generation of the fourth iteration of the read threshold voltage is further based at least in part on the characteristic, from (1) the first characteristic, (2) the second characteristic, and (3) the third characteristic, that is closest to the stored characteristic.

6. A system, comprising:

a storage read interface configured to:

perform a read of solid state storage, using a first iteration of a read threshold voltage that is set to a default voltage, in order to obtain a first characteristic associated with the first iteration of the read threshold voltage;

perform a read of the solid state storage, using a second iteration of the read threshold voltage, in order to obtain a second characteristic associated with the second iteration of the read threshold voltage; and

perform a read of the solid state storage, using a third iteration of the read threshold voltage, in order to obtain a third characteristic associated with the third iteration of the read threshold voltage; and

a voltage calculator configured to:

generate the second iteration of the read threshold voltage based at least in part on the default voltage and an offset;

generate the third iteration of the read threshold voltage based at least in part on the first characteristic and the second characteristic;

select, from (1) the first characteristic, (2) the second characteristic, and (3) the third characteristic, the two characteristics that are closest to a stored characteristic,

determine if the third characteristic is one of the two characteristics that are closest to the stored characteristic; and

in the event it is determined that the third characteristic is one of the two characteristics that are closest to the stored characteristic, generate a fourth iteration of the read threshold voltage based at least in part on the two characteristics that are closest to the stored characteristic.

7. The system of claim 6, wherein the first characteristic, the second characteristic, the third characteristic, and the stored characteristic include one or more of the following: a ratio of ones to zeros or a ratio of zeros to ones.

8. The system of claim 6, wherein the first characteristic, the second characteristic, the third characteristic, and the stored characteristic include one or more of the following: a number of ones or a number of zeros.

9. The system of claim 6, wherein the voltage calculator is further configured to: in the event it is determined that the third characteristic is not one of the two characteristics that are closest to the stored characteristic, generate the fourth iteration of the read threshold voltage based at least in part on the offset.

10. The system of claim 9, wherein the voltage calculator is further configured to: in the event it is determined that the third characteristic is not one of the two characteristics that are closest to the stored characteristic, generate the fourth iteration of the read threshold voltage further based at least in part on the characteristic, from (1) the first characteristic, (2) the second characteristic, and (3) the third characteristic, that is closest to the stored characteristic.

11. A computer program product, the computer program product being embodied in a non-transitory computer readable storage medium and comprising computer instructions for:

performing a read of solid state storage, using a first iteration of a read threshold voltage that is set to a default voltage, in order to obtain a first characteristic associated with the first iteration of the read threshold voltage;

generating a second iteration of the read threshold voltage based at least in part on the default voltage and an offset;

performing a read of the solid state storage, using the second iteration of the read threshold voltage, in order to obtain a second characteristic associated with the second iteration of the read threshold voltage;

generating a third iteration of the read threshold voltage based at least in part on the first characteristic and the second characteristic;

performing a read of the solid state storage, using the third iteration of the read threshold voltage, in order to obtain a third characteristic associated with the third iteration of the read threshold voltage;

selecting, from (1) the first characteristic, (2) the second characteristic, and (3) the third characteristic, the two characteristics that are closest to a stored characteristic, determining if the third characteristic is one of the two characteristics that are closest to the stored characteristic; and

in the event it is determined that the third characteristic is one of the two characteristics that are closest to the stored characteristic, generating a fourth iteration of the read threshold voltage based at least in part on the two characteristics that are closest to the stored characteristic.

12. The computer program product of claim 11, wherein the first characteristic, the second characteristic, the third

characteristic, and the stored characteristic include one or more of the following: a ratio of ones to zeros or a ratio of zeros to ones.

13. The computer program product of claim 11, wherein the first characteristic, the second characteristic, the third characteristic, and the stored characteristic include one or more of the following: a number of ones or a number of zeros. 5

14. The computer program product of claim 11 further comprising computer instructions for: in the event it is determined that the third characteristic is not one of the two characteristics that are closest to the stored characteristic, generating the fourth iteration of the read threshold voltage based at least in part on the offset. 10

15. The computer program product of claim 14 further comprising computer instructions for: in the event it is determined that the third characteristic is not one of the two characteristics that are closest to the stored characteristic, generating the fourth iteration of the read threshold voltage further based at least in part on the characteristic, from (1) the first characteristic, (2) the second characteristic, and (3) the third characteristic, that is closest to the stored characteristic. 15 20

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